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Power System Dynamics and Stability

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7

Power System Stability

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This introductory section provides a general description of the power system stability phenomena including fundamental concepts, classification, and definition of associated terms. A historical review of the emergence of different forms of stability problems as power systems evolved and of the developments of methods for their analysis and mitigation is presented. Requirements for consideration of stability in system design and operation are discussed.

7.1 Basic Concepts

Power system stability denotes the ability of an electric power system, for a given initial operating condition, to regain a state of operating equilibrium after being subjected to a physical disturbance, with most system variables bounded so that system integrity is preserved. Integrity of the system is preserved when practically the entire power system remains intact with no tripping of generators or loads, except for those disconnected by isolation of the faulted elements or intentionally tripped to preserve the continuity of operation of the rest of the system. Stability is a condition of equilibrium between opposing forces; instability results when a disturbance leads to a sustained imbalance between the opposing forces.

The power system is a highly nonlinear system that operates in a constantly changing environment; loads, generator outputs, topology, and key operating parameters change continually. When subjected to a transient disturbance, the stability of the system depends on the nature of the disturbance as well as the initial operating condition. The disturbance may be small or large. Small disturbances in the form of load changes occur continually, and the system adjusts to the changing conditions. The system must be able to operate satisfactorily under these conditions and successfully meet the load demand. It must also be able to survive numerous disturbances of a severe nature, such as a short-circuit on a transmission line or loss of a large generator.

Following a transient disturbance, if the power system is stable, it will reach a new equilibrium state with practically the entire system intact; the actions of automatic controls and possibly human operators will eventually restore the system to normal state. On the other hand, if the system is unstable, it will result in a run-away or run-down situation; for example, a progressive increase in angular separation of

generator rotors, or a progressive decrease in bus voltages. An unstable system condition could lead to cascading outages and a shut-down of a major portion of the power system.

The response of the power system to a disturbance may involve much of the equipment. For instance, a fault on a critical element followed by its isolation by protective relays will cause variations in power flows, network bus voltages, and machine rotor speeds; the voltage variations will actuate both generator and transmission network voltage regulators; the generator speed variations will actuate prime mover governors; and the voltage and frequency variations will affect the system loads to varying degrees depending on their individual characteristics. Further, devices used to protect individual equipment may respond to variations in system variables and thereby affect the power system performance. A typical modern power system is thus a very high-order multivariable process whose dynamic performance is influenced by a wide array of devices with different response rates and characteristics. Hence, instability in a power system may occur in many different ways depending on the system topology, operating mode, and the form of the disturbance.

Traditionally, the stability problem has been one of maintaining synchronous operation. Since power systems rely on synchronous machines for generation of electrical power, a necessary condition for satisfactory system operation is that all synchronous machines remain in synchronism or, colloquially, “in step.” This aspect of stability is influenced by the dynamics of generator rotor angles and power-angle relationships.

Instability may also be encountered without the loss of synchronism. For example, a system consisting of a generator feeding an induction motor can become unstable due to collapse of load voltage. In this instance, it is the stability and control of voltage that is the issue, rather than the maintenance of synchronism. This type of instability can also occur in the case of loads covering an extensive area in a large system.

In the event of a significant load/generation mismatch, generator and prime mover controls become important, as well as system controls and special protections. If not properly coordinated, it is possible for the system frequency to become unstable, and generating units and/or loads may ultimately be tripped possibly leading to a system blackout. This is another case where units may remain in synchronism (until tripped by such protections as under-frequency), but the system becomes unstable.

Because of the high dimensionality and complexity of stability problems, it is essential to make simplifying assumptions and to analyze specific types of problems using the right degree of detail of system representation. The following subsection describes the classification of power system stability into different categories.

7.2 Classification of Power System Stability

7.2.1 Need for Classification

Power system stability is a single problem; however, it is impractical to deal with it as such. Instability of the power system can take different forms and is influenced by a wide range of factors. Analysis of stability problems, including identifying essential factors that contribute to instability and devising methods of improving stable operation is greatly facilitated by classification of stability into appropriate categories. These are based on the following considerations (Kundur, 1994; Kundur and Morison, 1997):

- The physical nature of the resulting instability related to the main system parameter in which instability can be observed.
- The size of the disturbance considered indicates the most appropriate method of calculation and prediction of stability.
- The devices, processes, and the time span that must be taken into consideration in order to determine stability.

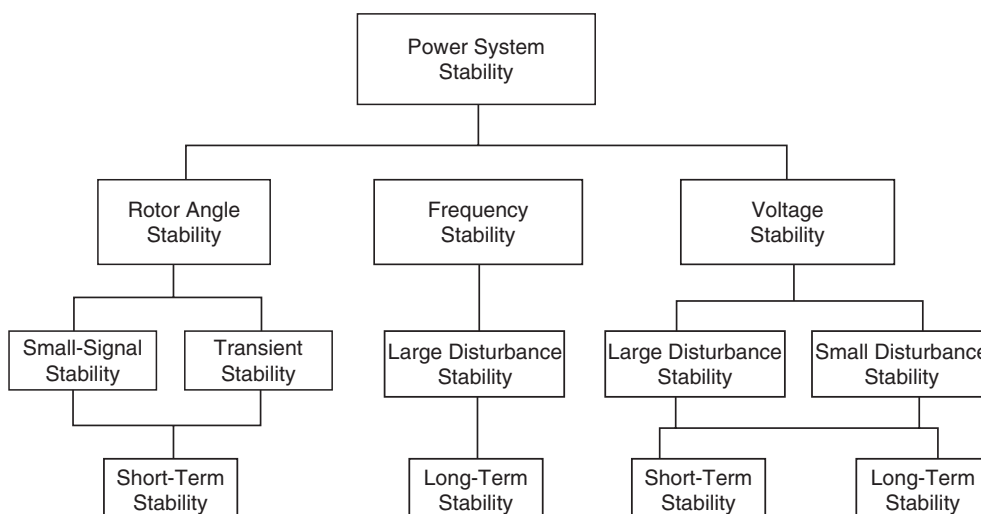


FIGURE 7.1 Classification of power system stability.

Figure 7.1 shows a possible classification of power system stability into various categories and subcategories. The following are descriptions of the corresponding forms of stability phenomena.

7.2.2 Rotor Angle Stability

Rotor angle stability is concerned with the ability of interconnected synchronous machines of a power system to remain in synchronism under normal operating conditions and after being subjected to a disturbance. It depends on the ability to maintain/restore equilibrium between electromagnetic torque and mechanical torque of each synchronous machine in the system. Instability that may result occurs in the form of increasing angular swings of some generators leading to their loss of synchronism with other generators.

The rotor angle stability problem involves the study of the electromechanical oscillations inherent in power systems. A fundamental factor in this problem is the manner in which the power outputs of synchronous machines vary as their rotor angles change. The mechanism by which interconnected synchronous machines maintain synchronism with one another is through restoring forces, which act whenever there are forces tending to accelerate or decelerate one or more machines with respect to other machines. Under steady-state conditions, there is equilibrium between the input mechanical torque and the output electrical torque of each machine, and the speed remains constant. If the system is perturbed, this equilibrium is upset, resulting in acceleration or deceleration of the rotors of the machines according to the laws of motion of a rotating body. If one generator temporarily runs faster than another, the angular position of its rotor relative to that of the slower machine will advance. The resulting angular difference transfers part of the load from the slow machine to the fast machine, depending on the power-angle relationship. This tends to reduce the speed difference and hence the angular separation. The power-angle relationship, as discussed above, is highly nonlinear. Beyond a certain limit, an increase in angular separation is accompanied by a decrease in power transfer; this increases the angular separation further and leads to instability. For any given situation, the stability of the system depends on whether or not the deviations in angular positions of the rotors result in sufficient restoring torques.

It should be noted that loss of synchronism can occur between one machine and the rest of the system, or between groups of machines, possibly with synchronism maintained within each group after separating from each other.

The change in electrical torque of a synchronous machine following a perturbation can be resolved into two components:

- *Synchronizing torque* component, in phase with a rotor angle perturbation.
- *Damping torque* component, in phase with the speed deviation.

System stability depends on the existence of both components of torque for each of the synchronous machines. Lack of sufficient synchronizing torque results in *aperiodic* or *non-oscillatory instability*, whereas lack of damping torque results in *oscillatory instability*.

For convenience in analysis and for gaining useful insight into the nature of stability problems, it is useful to characterize rotor angle stability in terms of the following two categories:

1. *Small signal* (or *steady state*) *stability* is concerned with the ability of the power system to maintain synchronism under small disturbances. The disturbances are considered to be sufficiently small that linearization of system equations is permissible for purposes of analysis. Such disturbances are continually encountered in normal system operation, such as small changes in load.

Small signal stability depends on the initial operating state of the system. Instability that may result can be of two forms: (i) increase in rotor angle through a non-oscillatory or aperiodic mode due to lack of synchronizing torque, or (ii) rotor oscillations of increasing amplitude due to lack of sufficient damping torque.

In today's practical power systems, small signal stability is largely a problem of insufficient damping of oscillations. The time frame of interest in small-signal stability studies is on the order of 10 to 20 s following a disturbance. The stability of the following types of oscillations is of concern:

- *Local modes* or *machine-system modes*, associated with the swinging of units at a generating station with respect to the rest of the power system. The term "local" is used because the oscillations are localized at one station or a small part of the power system.
- *Interarea modes*, associated with the swinging of many machines in one part of the system against machines in other parts. They are caused by two or more groups of closely coupled machines that are interconnected by weak ties.
- *Control modes*, associated with generating units and other controls. Poorly tuned exciters, speed governors, HVDC converters, and static var compensators are the usual causes of instability of these modes.
- *Torsional modes*, associated with the turbine-generator shaft system rotational components. Instability of torsional modes may be caused by interaction with excitation controls, speed governors, HVDC controls, and series-capacitor-compensated lines.

2. *Large disturbance rotor angle stability* or *transient stability*, as it is commonly referred to, is concerned with the ability of the power system to maintain synchronism when subjected to a severe transient disturbance. The resulting system response involves large excursions of generator rotor angles and is influenced by the nonlinear power-angle relationship.

Transient stability depends on both the initial operating state of the system and the severity of the disturbance. Usually, the disturbance alters the system such that the post-disturbance steady state operation will be different from that prior to the disturbance. Instability is in the form of aperiodic drift due to insufficient synchronizing torque, and is referred to as *first swing stability*. In large power systems, transient instability may not always occur as first swing instability associated with a single mode; it could be as a result of increased peak deviation caused by superposition of several modes of oscillation causing large excursions of rotor angle beyond the first swing.

The time frame of interest in transient stability studies is usually limited to 3 to 5 sec following the disturbance. It may extend to 10 sec for very large systems with dominant inter-area swings.

Power systems experience a wide variety of disturbances. It is impractical and uneconomical to design the systems to be stable for every possible contingency. The design contingencies are selected on the basis that they have a reasonably high probability of occurrence.

As identified in Fig. 7.1, small signal stability as well as transient stability are categorized as short term phenomena.

7.2.3 Voltage Stability

Voltage stability is concerned with the ability of a power system to maintain steady voltages at all buses in the system under normal operating conditions, and after being subjected to a disturbance. Instability that may result occurs in the form of a progressive fall or rise of voltage of some buses. The possible outcome of voltage instability is loss of load in the area where voltages reach unacceptably low values, or a loss of integrity of the power system.

Progressive drop in bus voltages can also be associated with rotor angles going out of step. For example, the gradual loss of synchronism of machines as rotor angles between two groups of machines approach or exceed 180° would result in very low voltages at intermediate points in the network close to the electrical center (Kundur, 1994). In contrast, the type of sustained fall of voltage that is related to voltage instability occurs where rotor angle stability is not an issue.

The main factor contributing to voltage instability is usually the voltage drop that occurs when active and reactive power flow through inductive reactances associated with the transmission network; this limits the capability of transmission network for power transfer. The power transfer limit is further limited when some of the generators hit their reactive power capability limits. The driving force for voltage instability are the loads; in response to a disturbance, power consumed by the loads tends to be restored by the action of distribution voltage regulators, tap changing transformers, and thermostats. Restored loads increase the stress on the high voltage network causing more voltage reduction. A run-down situation causing voltage instability occurs when load dynamics attempts to restore power consumption beyond the capability of the transmission system and the connected generation (Kundur, 1994; Taylor, 1994; Van Cutsem and Vournas, 1998).

While the most common form of voltage instability is the progressive drop in bus voltages, the possibility of overvoltage instability also exists and has been experienced at least on one system (Van Cutsem and Mailhot, 1997). It can occur when EHV transmission lines are loaded significantly below surge impedance loading and underexcitation limiters prevent generators and/or synchronous condensers from absorbing the excess reactive power. Under such conditions, transformer tap changers, in their attempt to control load voltage, may cause voltage instability.

Voltage stability problems may also be experienced at the terminals of HVDC links. They are usually associated with HVDC links connected to weak AC systems (CIGRE Working Group 14.05, 1992). The HVDC link control strategies have a very significant influence on such problems.

As in the case of rotor angle stability, it is useful to classify voltage stability into the following subcategories:

1. *Large disturbance voltage stability* is concerned with a system's ability to control voltages following large disturbances such as system faults, loss of generation, or circuit contingencies. This ability is determined by the system-load characteristics and the interactions of both continuous and discrete controls and protections. Determination of large disturbance stability requires the examination of the nonlinear dynamic performance of a system over a period of time sufficient to capture the interactions of such devices as under-load transformer tap changers and generator field-current limiters. The study period of interest may extend from a few seconds to tens of minutes. Therefore, long term dynamic simulations are required for analysis (Van Cutsem et al., 1995).
2. *Small disturbance voltage stability* is concerned with a system's ability to control voltages following small perturbations such as incremental changes in system load. This form of stability is determined by the characteristics of loads, continuous controls, and discrete controls at a given instant of time. This concept is useful in determining, at any instant, how the system voltage will respond to small system changes. The basic processes contributing

to small disturbance voltage instability are essentially of a steady state nature. Therefore, static analysis can be effectively used to determine stability margins, identify factors influencing stability, and examine a wide range of system conditions and a large number of postcontingency scenarios (Gao et al., 1992). A criterion for small disturbance voltage stability is that, at a given operating condition for every bus in the system, the bus voltage magnitude increases as the reactive power injection at the same bus is increased. A system is voltage unstable if, for at least one bus in the system, the bus voltage magnitude (V) decreases as the reactive power injection (Q) at the same bus is increased. In other words, a system is voltage stable if V - Q sensitivity is positive for every bus and unstable if V - Q sensitivity is negative for at least one bus.

The time frame of interest for voltage stability problems may vary from a few seconds to tens of minutes. Therefore, voltage stability may be either a short-term or a long-term phenomenon.

Voltage instability does not always occur in its pure form. Often, the rotor angle instability and voltage instability go hand in hand. One may lead to the other, and the distinction may not be clear. However, distinguishing between angle stability and voltage stability is important in understanding the underlying causes of the problems in order to develop appropriate design and operating procedures.

7.2.4 Frequency Stability

Frequency stability is concerned with the ability of a power system to maintain steady frequency within a nominal range following a severe system upset resulting in a significant imbalance between generation and load. It depends on the ability to restore balance between system generation and load, with minimum loss of load.

Severe system upsets generally result in large excursions of frequency, power flows, voltage, and other system variables, thereby invoking the actions of processes, controls, and protections that are not modeled in conventional transient stability or voltage stability studies. These processes may be very slow, such as boiler dynamics, or only triggered for extreme system conditions, such as volts/hertz protection tripping generators. In large interconnected power systems, this type of situation is most commonly associated with islanding. Stability in this case is a question of whether or not each island will reach an acceptable state of operating equilibrium with minimal loss of load. It is determined by the overall response of the island as evidenced by its mean frequency, rather than relative motion of machines. Generally, frequency stability problems are associated with inadequacies in equipment responses, poor coordination of control and protection equipment, or insufficient generation reserve. Examples of such problems are reported by Kundur et al. (1985); Chow et al. (1989); and Kundur (1981).

Over the course of a frequency instability, the characteristic times of the processes and devices that are activated by the large shifts in frequency and other system variables will range from a matter of seconds, corresponding to the responses of devices such as generator controls and protections, to several minutes, corresponding to the responses of devices such as prime mover energy supply systems and load voltage regulators.

Although frequency stability is impacted by fast as well as slow dynamics, the overall time frame of interest extends to several minutes. Therefore, it is categorized as a long-term phenomenon in Fig. 7.1.

7.2.5 Comments on Classification

The classification of stability has been based on several considerations so as to make it convenient for identification of the causes of instability, the application of suitable analysis tools, and the development of corrective measures appropriate for a specific stability problem. There clearly is some overlap between the various forms of instability, since as systems fail, more than one form of instability may ultimately emerge. However, a system event should be classified based primarily on the dominant initiating phenomenon, separated into those related primarily with voltage, rotor angle, or frequency.

While classification of power system stability is an effective and convenient means to deal with the complexities of the problem, the overall stability of the system should always be kept in mind. Solutions to stability problems of one category should not be at the expense of another. It is essential to look at all aspects of the stability phenomena, and at each aspect from more than one viewpoint.

7.3 Historical Review of Stability Problems

As electric power systems have evolved over the last century, different forms of instability have emerged as being important during different periods. The methods of analysis and resolution of stability problems were influenced by the prevailing developments in computational tools, stability theory, and power system control technology. A review of the history of the subject is useful for a better understanding of the electric power industry's practices with regard to system stability.

Power system stability was first recognized as an important problem in the 1920s (Steinmetz, 1920; Evans and Bergvall, 1924; Wilkins, 1926). The early stability problems were associated with remote power plants feeding load centers over long transmission lines. With slow exciters and noncontinuously acting voltage regulators, power transfer capability was often limited by steady-state as well as transient rotor angle instability due to insufficient synchronizing torque. To analyze system stability, graphical techniques such as the equal area criterion and power circle diagrams were developed. These methods were successfully applied to early systems which could be effectively represented as two machine systems.

As the complexity of power systems increased, and interconnections were found to be economically attractive, the complexity of the stability problems also increased and systems could no longer be treated as two machine systems. This led to the development in the 1930s of the network analyzer, which was capable of power flow analysis of multimachine systems. System dynamics, however, still had to be analyzed by solving the swing equations by hand using step-by-step numerical integration. Generators were represented by the classical "fixed voltage behind transient reactance" model. Loads were represented as constant impedances.

Improvements in system stability came about by way of faster fault clearing and fast acting excitation systems. Steady-state aperiodic instability was virtually eliminated by the implementation of continuously acting voltage regulators. With increased dependence on controls, the emphasis of stability studies moved from transmission network problems to generator problems, and simulations with more detailed representations of synchronous machines and excitation systems were required.

The 1950s saw the development of the analog computer, with which simulations could be carried out to study in detail the dynamic characteristics of a generator and its controls rather than the overall behavior of multimachine systems. Later in the 1950s, the digital computer emerged as the ideal means to study the stability problems associated with large interconnected systems.

In the 1960s, most of the power systems in the U.S. and Canada were part of one of two large interconnected systems, one in the east and the other in the west. In 1967, low capacity HVDC ties were also established between the east and west systems. At present, the power systems in North America form virtually one large system. There were similar trends in growth of interconnections in other countries. While interconnections result in operating economy and increased reliability through mutual assistance, they contribute to increased complexity of stability problems and increased consequences of instability. The Northeast Blackout of November 9, 1965, made this abundantly clear; it focused the attention of the public and of regulatory agencies, as well as of engineers, on the problem of stability and importance of power system reliability.

Until recently, most industry effort and interest has been concentrated on *transient (rotor angle) stability*. Powerful transient stability simulation programs have been developed that are capable of modeling large complex systems using detailed device models. Significant improvements in transient stability performance of power systems have been achieved through use of high-speed fault clearing, high-response exciters, series capacitors, and special stability controls and protection schemes.

The increased use of high response exciters, coupled with decreasing strengths of transmission systems, has led to an increased focus on *small signal (rotor angle) stability*. This type of angle instability is often seen as local plant modes of oscillation, or in the case of groups of machines interconnected by weak links, as interarea modes of oscillation. Small signal stability problems have led to the development of special study techniques, such as modal analysis using eigenvalue techniques (Martins, 1986; Kundur et al., 1990). In addition, supplementary control of generator excitation systems, static Var compensators, and HVDC converters is increasingly being used to solve system oscillation problems. There has also been a general interest in the application of power electronic based controllers referred to as FACTS (Flexible AC Transmission Systems) controllers for damping of power system oscillations (IEEE, 1996).

In the 1970s and 1980s, frequency stability problems experienced following major system upsets led to an investigation of the underlying causes of such problems and to the development of long term dynamic simulation programs to assist in their analysis (Davidson et al., 1975; Converti et al., 1976; Stubbe et al., 1989; Inoue et al., 1995; Ontario Hydro, 1989). The focus of many of these investigations was on the performance of thermal power plants during system upsets (Kundur et al., 1985; Chow et al., 1989; Kundur, 1981; Younkins and Johnson, 1981). Guidelines were developed by an IEEE Working Group for enhancing power plant response during major frequency disturbances (1983). Analysis and modeling needs of power systems during major frequency disturbances was also addressed in a recent CIGRE Task Force report (1999).

Since the late 1970s, voltage instability has been the cause of several power system collapses worldwide (Kundur, 1994; Taylor, 1994; IEEE, 1990). Once associated primarily with weak radial distribution systems, voltage stability problems are now a source of concern in highly developed and mature networks as a result of heavier loadings and power transfers over long distances. Consequently, voltage stability is increasingly being addressed in system planning and operating studies. Powerful analytical tools are available for its analysis (Van Cutsem et al., 1995; Gao et al., 1992; Morison et al., 1993), and well-established criteria and study procedures are evolving (Abed, 1999; Gao et al., 1996).

Present-day power systems are being operated under increasingly stressed conditions due to the prevailing trend to make the most of existing facilities. Increased competition, open transmission access, and construction and environmental constraints are shaping the operation of electric power systems in new ways that present greater challenges for secure system operation. This is abundantly clear from the increasing number of major power-grid blackouts that have been experienced in recent years; for example, Brazil blackout of March 11, 1999; Northeast USA-Canada blackout of August 14, 2003; Southern Sweden and Eastern Denmark blackout of September 23, 2003; and Italian blackout of September 28, 2003. Planning and operation of today's power systems require a careful consideration of all forms of system instability. Significant advances have been made in recent years in providing the study engineers with a number of powerful tools and techniques. A coordinated set of complementary programs, such as the one described by Kundur et al. (1994) makes it convenient to carry out a comprehensive analysis of power system stability.

7.4 Consideration of Stability in System Design and Operation

For reliable service, a power system must remain intact and be capable of withstanding a wide variety of disturbances. Owing to economic and technical limitations, no power system can be stable for all possible disturbances or contingencies. In practice, power systems are designed and operated so as to be stable for a selected list of contingencies, normally referred to as "design contingencies" (Kundur, 1994). Experience dictates their selection. The contingencies are selected on the basis that they have a significant probability of occurrence and a sufficiently high degree of severity, given the large number of elements comprising the power system. The overall goal is to strike a balance between costs and benefits of achieving a selected level of system security.

While security is primarily a function of the physical system and its current attributes, secure operation is facilitated by:

- Proper selection and deployment of preventive and emergency controls.
- Assessing stability limits and operating the power system within these limits.

Security assessment has been historically conducted in an off-line operation planning environment in which stability for the near-term forecasted system conditions is exhaustively determined. The results of stability limits are loaded into look-up tables which are accessed by the operator to assess the security of a prevailing system operating condition.

In the new competitive utility environment, power systems can no longer be operated in a very structured and conservative manner; the possible types and combinations of power transfer transactions may grow enormously. The present trend is, therefore, to use online dynamic security assessment. This is feasible with today's computer hardware and stability analysis software. (Morison et al., 2004).

In addition to online dynamic security assessment, a wide range of other new and emerging technologies could assist in significantly minimizing the occurrence and impact of widespread blackouts. These include:

- Risk-based system security assessment
- Adaptive relaying
- Wide-area monitoring and control
- Flexible AC Transmission (FACTS) devices
- Distributed generation technologies

Acknowledgment

The definition and classification of power system stability presented in this section is based on the report prepared by a joint IEEE/CIGRE Task Force on Power System Stability Terms, Classification, and Definitions. This report has been published in the IEEE Transactions on Power Systems, August 2004 and as CIGRE Technical Brochure 231, June 2003.

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